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Data evaluation and numerical modeling of hydrological interactions between active layer, lake and talik in a permafrost catchment, Western Greenland

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SUMMARY

This study investigates annual water balance conditions and their spatiotemporal variability under a wide variety of atmospheric driving conditions in the periglacial permafrost catchment of Two Boat Lake in Western Greenland. The study uses and combines a comprehensive hydrological multi-parameter dataset measured at the site with site conceptualization and numerical model development, application and testing. The model result reproduces measured lake and groundwater levels, as well as observations made by time-lapse cameras. The results highlights the importance of numerical modeling that takes into account and combines evapotranspiration with other surface and subsurface hydrological processes at various depths, in order to quantitatively understand and represent the dynamics and complexity of the interactions between meteorology, active layer hydrology, lakes, and unfrozen groundwater below permafrost in periglacial catchments. Regarding these interactions, the water flow between the studied lake and a through talik within and beneath it is found to be small compared to other water balance components. The modeling results show that recharge and discharge conditions in the talik can shift in time, while the lake and active layer conditions in the studied catchment are independent of catchment-external landscape features, such as the unfrozen groundwater system below the permafrost and the nearby continental-scale ice sheet.

1. Introduction

Periglacial hydrology has during the last decade been a research topic of growing interest, especially in the climate change context. Permafrost soils and bedrock, which may contain significant fractions of ice, are highly sensitive to climate change. Climate-driven responses in landscapes, ecosystems and water systems may then be both heterogeneous and complex. A general lack of data and process understanding related to freezing and thawing processes in periglacial environments has been identified (Vaughan et al., 2013).

The hydrological cycle and water balance conditions of periglacial regions are influenced by ice, snow and frozen soil, with large seasonal fluctuations in the surface energy balance (Woo et al., 2008). The presence of permafrost, and its seasonal freeze and thaw processes may control the distribution and routing of water across the landscape (Quinton and Carey, 2008). Permafrost and its variability are therefore important for hydrological and water balance responses to change in high latitude areas (Kane et al., 1989; Hinzman et al., 1991; Karlsson et al., 2012). Sublimation has also been shown to be significant in the water balance of cold region environments (Reba et al., 2011; MacDonald et al., 2010) where the major part of the annual runoff is generated by snowmelt (McCann and Cogley, 1972). In general, the hydrological impacts of snow and surface and subsurface freezing processes accentuate the importance of including winter and spring measurements in hydrological and water balance assessments of catchments (Hirashima et al., 2004; Verrot and Destouni, 2015).

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Thorough water balance studies have been carried out for the near-surface hydrological system in the active layer of permafrost catchments (Søgaard and Hasholt, 2001; Woo and Marsh, 2005; Helbig et al., 2013), wetlands in permafrost areas (Jessen et al., 2014) and thermokarst lakes (Fedorov et al., 2014; Karlsson et al., 2014). With regard to the hydrogeology of cold regions, Hinzman et al. (2013) summarized the current status of research progress including regional studies (Cheng and Jin, 2013), process studies (Sjöberg et al., 2013) and simulation studies (Frampton et al., 2013; Wellman et al., 2013; McKenzie and Voss, 2013). However, the linking of surface hydrological processes to subsurface hydrology below the permafrost is not as well investigated. Even though groundwater recharge and discharge are reduced by the presence of permafrost, water exchange of deep and shallow groundwater through taliks exists and needs to be taken into consideration in catchments with permafrost (Bense et al., 2009; Frampton et al., 2011, 2013; Ge et al., 2011; Grenier et al., 2013; Bosson et al., 2012, 2013a; Kane et al., 2013). In a changing climate, talik growth might increase (Romanovsky et al., 2010; Vaughan et al., 2013) with increased contact between deep and shallow groundwaters as a consequence. Therefore, there is a need for an integrated approach in hydrological modeling that can take both supra- and sub-permafrost groundwaters into account.

To our best knowledge, only a few studies have considered the links and interactions between both surface and subsurface water, and shallow and deep groundwater for a whole catchment. However, a modeling study by Bosson et al. (2013a) investigated the exchange of shallow and deep groundwaters in a far-future colder Sweden. The modeling was based on simulated climate time series, but comparison to measurements could not be done for the possible future cold state of the investigated Swedish catchment. The present study uses a comprehensive dataset, presented in Johansson et al. (2015) for a periglacial catchment in Western Greenland, to test some key aspects of the modeling approach and simulation results of Bosson et al. (2013a). The catchment, which is called Two Boat Lake, drains into a lake underlain by a through talik and is located in an area with continuous permafrost.

By use of the collected dataset and applied numerical modeling, this study aims to analyze the long-term water balance conditions and their spatial and intra-annual temporal variability, and to identify and quantify the main hydrological flow paths and processes in the permafrost catchment of Two Boat Lake. The study uses and combines meteorological and hydrological data on surface water and groundwater levels, along with conceptual site and process understanding, to construct and calibrate a numerical model that quantifies the catchment scale hydrology and hydrogeology.

Methodologically, the annual thawing and freezing dynamics of the active layer and its influence on hydrological flows are represented in the modeling by soil temperature and its influence on hydraulic properties; this uses the same modeling approach as Bosson et al. (2010, 2012) and tests it against the available dataset. In particular, the numerical modeling approach of Bosson et al. (2010, 2012) used time-varying hydraulic properties, instead of a thermal model component, in order to describe thawing and freezing processes; the present study tests this approach on site-specific data from the Two Boat Lake permafrost catchment.

2. Materials and methods

2.1. Methodology

The investigated catchment of Two Boat Lake (TBL) in the Kangerlussuaq area, Western Greenland, is characterized by a dry climate, where running surface water that is not related to glacial melt is uncommon. Site investigations in the catchment were initiated in 2010 and have resulted in a wealth of information on the catchment hydrology and local meteorological conditions constituting the basis for the conceptual and numerical modeling described in the present paper. Discharge measurements of surface water are often a keystone in water balance studies for calibrating hydrological models, but such measurements could not be performed in the dry TBL catchment. The measurement installations, sampling and resulting data for the TBL catchment (until December 31, 2013) are described in detail in Johansson et al. (2015). The methodology employed in the present study is illustrated in Fig. 1 and includes: (i) constructing a conceptual and numerical hydrological model of the TBL area, (ii) calculating the water balance of the TBL catchment for different time periods, and (iii) studying the intra-annual hydrological interactions of the active layer, lake and talik.

All available data from the site are used in the analysis and conceptualization (A and B in Fig. 1). The methodology for modeling permafrost dynamics in MIKE SHE (Graham and Butts, 2005), which is the numerical modeling tool used in the present study, is described in Bosson et al. (2012). This methodology together with the conceptual model and site data are used to build up the numerical model (C in Fig. 1), which is calibrated and evaluated on an annual basis using data from the investigated period 2010–2013 (D in Fig. 1). The calibration targets of this first modeling stage are to reproduce the temporal pattern in the measured lake level variation and to achieve a water balance of the TBL catchment for the simulated period in accordance with observed values. A sensitivity analysis of (i) hydraulic properties in the active layer and bedrock and (ii) temperature-based time-varying processes in the active layer and on the ground surface are performed in order to reach these calibration targets.

In order to also relate the relatively short period of local data to long-term water balance conditions, 35 years of meteorological data from Kangerlussuaq (25 km from TBL) are used to define wet, dry and normal years with respect to precipitation (P). The three selected years are simulated using the calibrated model from stage one with the aim to analyze the sensitivity of the water balance components to weather conditions. In a last step, simulation results are also evaluated with respect to spatial and intra-annual temporal hydrological and hydrogeological variations within the catchment. In the following sections, the steps corresponding to each box B–F in Fig. 1 are described.

2.2. Site description and data overview

The TBL study catchment is situated approximately 25 km Northeast of the settlement Kangerlussuaq, in West Greenland (Fig. 2). This is the most extensive ice-free part of Greenland and includes a broad range of Arctic environments, from the coast, through plains and a hilly terrain, to the ice sheet margin. The

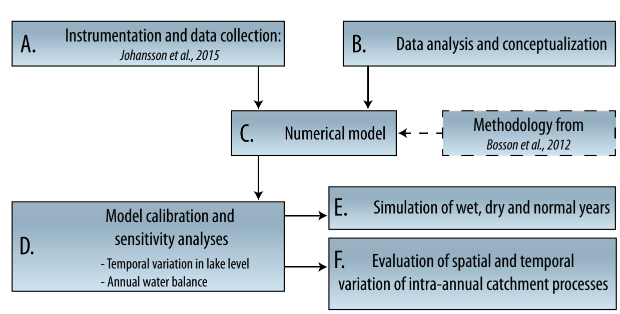

Fig. 1. Overall workflow from data collection to construction and evaluation of conceptual and numerical models of the hydrology and hydrogeology in the Two Boat Lake catchment, Western Greenland.